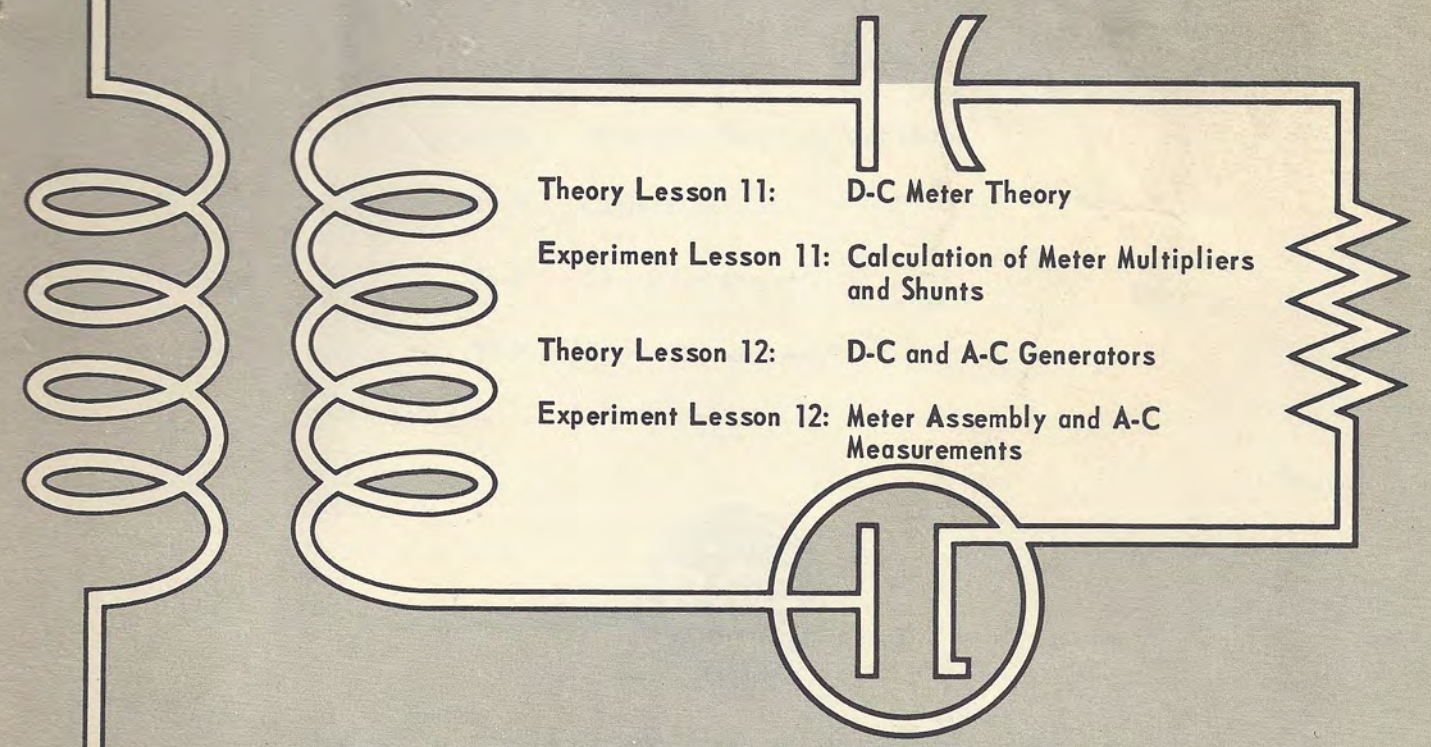


ELECTRONIC FUNDAMENTALS



Theory Lesson 11: D-C Meter Theory
Experiment Lesson 11: Calculation of Meter Multipliers and Shunts
Theory Lesson 12: D-C and A-C Generators
Experiment Lesson 12: Meter Assembly and A-C Measurements

RCA INSTITUTES, INC.

A SERVICE OF RADIO CORPORATION OF AMERICA
New York, N. Y.



ELECTRONIC FUNDAMENTALS

THEORY LESSON 11

D-C METER THEORY

- 11-1. Principles of Meter Movements
- 11-2. Meter Scale
- 11-3. Commercial Meter Movements
- 11-4. Movement Used as Voltmeter
- 11-5. Current Ranges
- 11-6. Ohmmeter Circuits
- 11-7. Power Measurement



RCA INSTITUTES, INC.

A SERVICE OF RADIO CORPORATION OF AMERICA

HOME STUDY SCHOOL

350 West 4th Street, New York 14, N. Y.

Theory Lesson 11

INTRODUCTION

Meters of one type or another are used in laboratories and radio and TV repair shops more often than any other kind of electrical test equipment. As a serviceman, you will use a meter more than any other kind of test equipment. You have already begun to use the d-c section of your multimeter to measure voltage, current, and resistance. As you use your meter to make other measurements, you will need to know something about how it works. The more you know about the circuit of your meter, the more intelligently you will use it. Also, you will want to know how to find trouble in the circuits and the movement of your meter if it becomes defective. In this lesson, you will learn about basic meter circuits and movements. (The circuits and movements of most meters are much the same as those that are used in your multimeter). Remember that repairs on the meter movement itself should be left in the hands of a skilled meter repairman.

11-1. PRINCIPLES OF METER MOVEMENTS

Motor Action. A brief explanation of motor action will help you understand how a meter movement works. In Fig. 11-1a, the cross section of a wire of nonmagnetic conducting metal, such as copper or aluminum, is shown in the field between the north and south poles of a permanent magnet. With no current through the wire, no motion is produced. However, if we pass a direct current through the wire, as shown in Fig. 11-1b, a magnetic field is produced around the wire. When the electrons in the wire come toward you, as shown, the lines of force have a clockwise direction. Let's see what happens

when the conductor and its field are placed in the field produced by the two fixed magnetic poles, as shown in Fig. 11-1c. As you know from your study of electromagnetism, flux lines that point in the same direction repel each other and those that point in opposite directions attract each other. So, the movable conductor travels in the direction shown. Reversing the polarity of *either* of the two magnetic fields will reverse the direction of the mechanical force, but reversing the polarity of *both* fields will keep the force in the same direction.

The forces that cause the coil to move depend on three factors: the strength of the moving coil field, the strength of the permanent-magnet field, and the placement of the coil in the field. If the strength of either field is increased, the force acting on the moving coil is increased. The strength of the permanent-magnet field can be increased by using a stronger magnet. The strength of the moving coil field may be increased in three ways:

1. By increasing the amount of current flowing in the moving coil

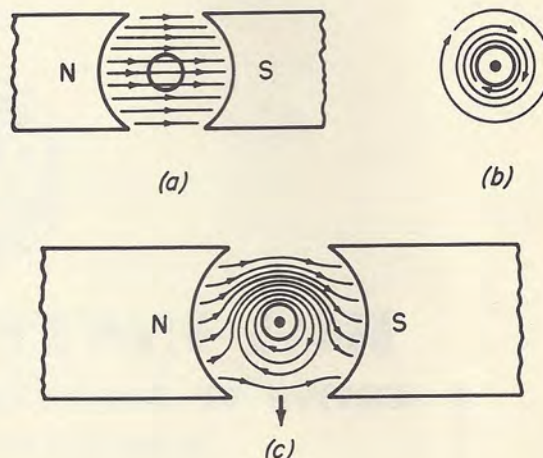


Fig. 11-1

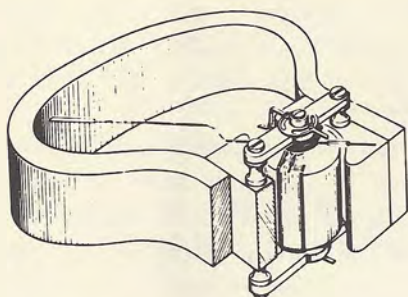


Fig. 11-2

2. By increasing the number of turns in the moving coil

3. By using a core with less reluctance (greater permeability) in the moving coil

The force acting on the moving coil is greatest when the turns are at right angles (90 degrees) to the lines of force of the permanent magnet. This force becomes less as the angle is made less than 90 degrees. When the wire is exactly parallel to the lines of force of the permanent magnet, the force acting on the coil becomes zero.

D'Arsonval-Weston Meter Movement.

While the moving-coil meter movement is very often called the D'Arsonval movement, it is better called the D'Arsonval-Weston movement. In 1856, an English experimenter named Vanley received a patent on the first moving-coil movement. This first meter was not very sensitive and would not be of much use in making many of the measurements servicemen must make each day. However, a French scientist named D' Arsonval, working along the same basic principles, produced a much more sensitive meter movement. The only trouble with his movement was that it was so delicate that it could be used safely only in laboratories. It remained for Dr. Edward Weston, another Englishman, to develop the first moving-coil movement that was both sensitive enough and rugged enough for wide practical use. Modern moving-coil meter movements are much the same as Weston's meter. They differ from his mainly in the improved quality of the materials and methods used in making them. The moving-coil meter uses the action of two magnetic fields on each other. This is called

the motor principle. It is the same principle that is the basis of electric motors, relays, solenoids, and many other electromagnetic devices. Let's see exactly how this meter principle works in a D'Arsonval meter movement. A cutaway view of such a basic meter movement is shown in Fig. 11-2.

The horseshoe-shaped permanent magnet supplies the steady magnetic field to the gap in which the coil is supported. The soft iron pole pieces concentrate the magnetic field in the gap in which the coil moves. The pole pieces are shaped to keep the field intensity uniform in all parts of the gap, which is necessary if the scale of the instrument is to be linear. (A linear scale is one in which there is an equal distance between calibrations of the same units.) The soft-iron core of the coil is held in place by supports that do not interfere with the normal movement of the coil. The core completes the magnetic path between the pole pieces and makes the air gap in the magnetic circuit as short as possible.

The moving coil itself, shown in Fig. 11-3a, is wound of very fine insulated copper wire on a light *bobbin*, or frame, of thin aluminum. Two hard steel pivots, such as the one shown in Fig. 11-3b, are fastened to the bobbin, and their highly polished points rest in jewel bearings. The upper bearing is mounted in a bracket of nonmagnetic metal,

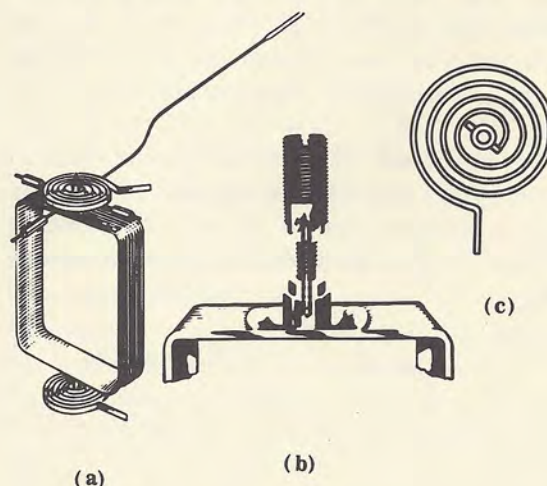


Fig. 11-3

which is fastened to the pole pieces. The other bearing is similarly mounted, but is hidden by the core. With this suspension, there is little friction for the coil to overcome as it rotates.

Meters with the pivot-and-jewel suspension can stand the normal jars and vibration met in everyday use and handling, but they should be treated with the same care you would give a fine watch.

The springs at either end of the coil are very important parts of the meter. One spring is shown separately in Fig. 11-3c. The current is conducted through the springs to the coil. The springs also supply the mechanical force for returning the coil to its original position after the current stops flowing. These springs operate like the door checks or door springs that you've seen on doors. When a door with such a spring is opened, the spring opposes the opening force. As soon as the force is removed, the spring acts to close the door. Not only does the spring close the door, but it also keeps the door from swinging open too far. The spiral springs in the meter movement have the same two effects on the moving coil; they keep the coil from swinging too far and they return the coil to its original position after a measurement has been made.

The meter pointer is attached to the coil. When the coil moves, the meter pointer moves with it. When the coil is in its original position (not moved) the metal pointer points to zero on the meter scale.

An important point about the springs is that they are spiralled in opposite directions. This is done so that if there is any change in their length or stiffness, due to age or changes of temperature, the changes will balance each other out and not change the zero-current position of the coil. The springs must also be good conductors and nonmagnetic so that the accuracy of the meter will not be affected. The springiness of the springs should remain the same with age and with normal changes in temperature. If the springs become weaker, they will allow the

coil, and, therefore, the meter pointer, to reach a given scale reading with less current than if the springs were at full strength.

Friction in the movement is never desirable, but it is much more serious if the friction is not the same at all points in the travel of the moving parts or if it varies in different positions of the moving parts or at different temperatures. However, the design and mechanical perfection of the jewel bearings in even a moderately priced instrument are so good that usually the slight friction is not important. However, even the best of instruments may develop friction if abused; therefore it pays to be careful when you use your meter. In Service Practices 8, a method of testing for friction and other troubles in meter movements is given.

The *inertia* of the movement is very important too. Inertia is the opposition that a body offers to any change in motion. If a body is not moving, inertia tends to keep it from moving; if a body is moving, inertia tends to keep it from stopping. For example, an automobile needs a lot of power to overcome inertia when starting up from a position of rest. It needs plenty of braking power in order to stop it once it is in motion. The inertia of a meter movement depends upon the weight of the whole moving-coil assembly and the distribution of that weight around the turning axis. It is very desirable to keep the inertia of the movement as low as possible. The lower the inertia, the more quickly the coil will turn to the final reading, and the less it will tend to swing back and forth past the actual final reading before settling down. If the movement is at rest, the movement cannot move instantly to the reading, any more than a car, in starting, can leap instantly to full speed when you step on the gas. So the meter movement must be speeded up from zero speed to the speed at which it swings to the reading; this takes force, and time. Also, once the movement is swinging, force will be required to bring it to a stop at the end of the swing. The lower the weight of the moving-coil assembly, the less trouble there will be from inertia. In commercial meters of good

design, the total weight of the moving system, including the pointer, is often a very small part of an ounce, even though the movement may be made up of as many as sixteen separate parts.

Damping. In good meters, the amount of overswing in coming to a reading is reduced by electrical or mechanical *damping*. Damping is the retarding or checking of the swinging motion of the coil. Without damping, the needle would tend to swing back and forth until it gradually came to rest at the proper point on the meter scale. In one system of electrical damping, a magnetic field is produced around the aluminum frame of the moving coil. This field is always in a direction that opposes the permanent magnet field, and it tends to oppose the movement of the coil. In practical instruments, damping usually lets the pointer reach its final rest position quickly, with very little overswing. This makes the meter more convenient to use and also reduces the likelihood of damage when the pointer is driven off scale by reversed polarity or moderate overcurrent.

Meter Accuracy. Most makers of moving-coil meters state the accuracy of the meter as a percentage of full-scale reading. For meters of moderate price, the accuracy will usually be about plus or minus two percent ($\pm 2\%$). For laboratory-standard purposes, careful hand adjustment and calibration can provide meters reliable to within one-half of one percent, or even one-tenth of one percent. Of course, the over-all accuracy of an instrument like a multimeter depends not only on the accuracy of the basic movement, but on the accuracy of other parts of the circuit as well.

Meter Sensitivity. When choosing a meter to buy and use, remember that the sensitivity of a meter has a great deal to do with its usefulness. An instrument that requires 10 to 20 milliamperes to give a full-scale reading is useless for measuring a current of one or two microamperes. However, the cost of meters usually goes up with the sensitivity. Thus, it would be a waste of money to use a meter that reads full-scale on 50 microam-

peres for measurements in which the lowest reading will never be less than several milliamperes.

Sensitivity is actually a way of saying how much current must flow through the coil to produce a swing of the indicating needle to full scale. Usually, sensitivity is spoken of in milliamperes or microamperes. A good meter movement for a volt-ohm-milliammeter of the type commonly used in radio work will require 50 microamperes for a full-scale reading. This sensitivity is expressed in *ohms-per-volt* when the whole instrument is considered as a voltmeter. For example, the movement of your multimeter is rated at 50 microamperes, or 20,000 ohms-per-volt.

The sensitivity of a movement is determined by the magnetic flux in the gap in which the coil moves, the number of turns of wire in the coil, the resistance of the coil, the elasticity of the springs, and the friction in the pivots. If it were practical to double the number of turns in the coil without changing the resistance, only one-half as much current would be required to force the pointer to full scale. However, in order to double the number of turns without any change in resistance, it is necessary to use wire of double the cross-sectional area. A coil wound with such wire will weigh four times as much and will take considerably more space. The added weight will put more load on the bearings. Therefore, it will increase the friction and add to the inertia. A more practical way to get greater sensitivity is by increasing the strength of the magnet instead of adding turns to the coil. Today it is possible to have practical, portable multimeters that reach full-scale readings on as small a current as 10 microamperes. Used as a voltmeter, the same instruments have a sensitivity of 100,000 ohms-per-volt.

11-2. METER SCALE

The most desirable meter scale is one that is linear. A linear scale, you remember, is one in which the marks on the scale are equally spaced. For example, with a linear scale, each time the current is increased by



Fig. 11-4

5 ma, the needle moves an equal distance from one calibration to the next. In order that the needle be deflected an equal amount for an equal amount of current, it is necessary that the magnetic field in which the coil moves be of uniform strength in all angles through which the coil moves from zero to full scale. A linear scale is shown in Fig. 11-4. Good meters usually have linear d-c scales that are accurate enough to make it possible to print scales for all meters of a given model on a printing press. However, the scales of laboratory instruments are often hand-calibrated for each individual instrument, giving a slightly better over-all accuracy.

The accuracy of the calibration of the original model of a given instrument affects the accuracy of each unit produced. Usually, several models of the meter to be produced are hand calibrated, and the calibrations are averaged in preparing the final scales to be printed. In this way, all movements will be within a certain tolerance, so far as scale errors are concerned. The thickness of scale markings affect the accuracy of the actual reading. Very thick markings are easy to see, but they increase the error in reading.

The scales of general-purpose instruments are made with reasonably heavy lines. The hand-calibrated scales of a precision laboratory instrument usually have considerably finer lines. The thickness of the needle pointer also affects the accuracy with which a meter can be read. Laboratory instruments usually have thin pointers.

11-3. COMMERCIAL METER MOVEMENTS

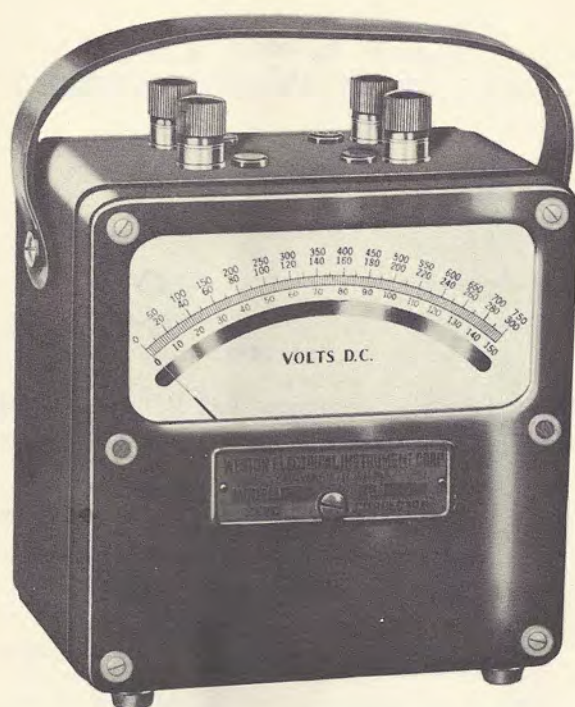
A typical commercial meter is shown in Fig. 11-5a. A skeleton view of the movement

of the same meter is shown in Fig. 11-5b. Most of the parts shown have been described already. However, let us discuss the zero-adjusting device, the needle or pointer, the needle stops, and the case or container for the movement.

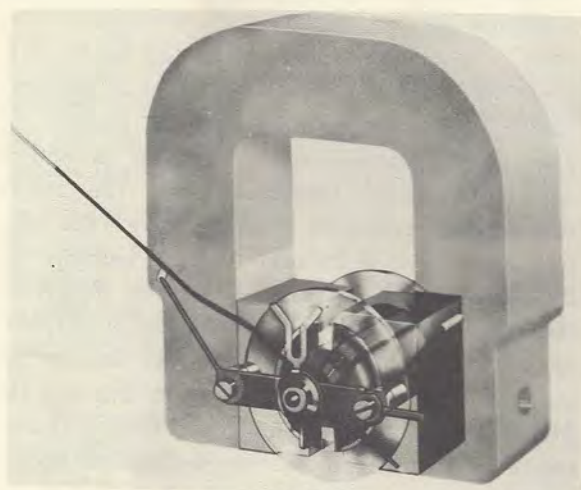
The zero-adjusting device is used to bring the meter needle over the zero mark on the meter scale. This adjustment is made by turning the zero-adjust screw-head on the front panel of the meter until the meter needle is in the proper position. The screw-head that is turned is actually the slotted head of the adjusting rod. This adjusting rod is connected with the bracket that holds the moving coil. The bracket and the coil are connected with springs. When the adjusting rod is turned, it moves the bracket and the coil. Therefore, the meter needle moves. Once the needle is so adjusted, this adjustment seldom has to be made again, unless the meter is roughly handled or driven hard off scale.

The needle, or pointer, is usually a very light tubular shaft made of an aluminum alloy. The part of the needle that actually extends over the dial scales has a thin knife-blade shape to permit accurate reading. Sometimes the blade-shaped portion of the pointer is a separate piece fastened to the tubular shaft. This piece, called the blade, is often made extra wide in order to increase the air resistance that the needle meets in swinging through the narrow space between the scale card and the protective glass. This air resistance adds some mechanical damping to help control overswing of the needle.

The stops in practical meters are usually two wire brackets fastened to the movement in such a way that they mechanically stop the needle from swinging more than a few degrees off scale in either direction. These stops are usually padded; a piece of rubber or other insulating tubing is slipped over the part that actually meets the needle to minimize wear and shock to the movement when needle is pinned by reversed polarity or too much current.



(a)



(b)

Fig. 11-5

In most practical commercial meters, the entire movement is mounted in a plastic or metal case. The face is visible through a window of glass or plastic. This aids in protecting the movement from dust, heat, and tampering, improves the appearance of the meter, and makes it more convenient to mount the movement.

Sensitivity. Useful as a simple moving-coil meter may be, it is far more useful

when combined with certain parts, such as resistors, switches, and rectifiers. We know that the basic meter movement is designed to move the pointer to full-scale position when a certain amount of current flows through the moving coil. The amount of current necessary to force the pointer to full scale may be in amperes, milliamperes, or in microamperes, depending upon the sensitivity of the movement. Your meter movement, for example, needs only 50 microamperes to go full scale. However, many multimeters use a basic 1-ma movement. With such a movement, the pointer is at full scale when a current of 1 ma flows through the moving coil. Of course, a voltage must be placed across the moving coil for a current to flow. The amount of voltage depends on the resistance of the coil.

Meter Resistance. Because it is difficult to make two coils exactly alike, the resistance of one moving coil may not be the same as the resistance of the next coil made by the same operator for the same meter model. The difference in resistance may be only an ohm or two, or it may be as much as twenty or thirty ohms. In order that all meter movements of the same model have the same resistance, it is necessary to add some resistance in series with the moving coil to bring the total resistance up to some standard amount. For example, Fig. 11-6a shows a meter with a moving coil resistance (R_c) of 276 ohms. The standard resistance for this meter model has been set at 300 ohms. To bring this movement up to the standard, it is necessary to add a 24-ohm resistor. This resistor is called the *standardizing resistor* and is marked R_s in the drawing. However, the meter movement shown in Fig. 11-6b has a 281-ohm moving coil. The standardizing resistor for this movement has a value of 19 ohms. Not all 1-ma movements have a standard resistance of 300 ohms; the standard varies with different models and different manufacturers. Neither do all meter movements meet an exact standard of resistance. Some meter movements may vary slightly from the standard. However, because meter accuracy is affected by several factors in addition to

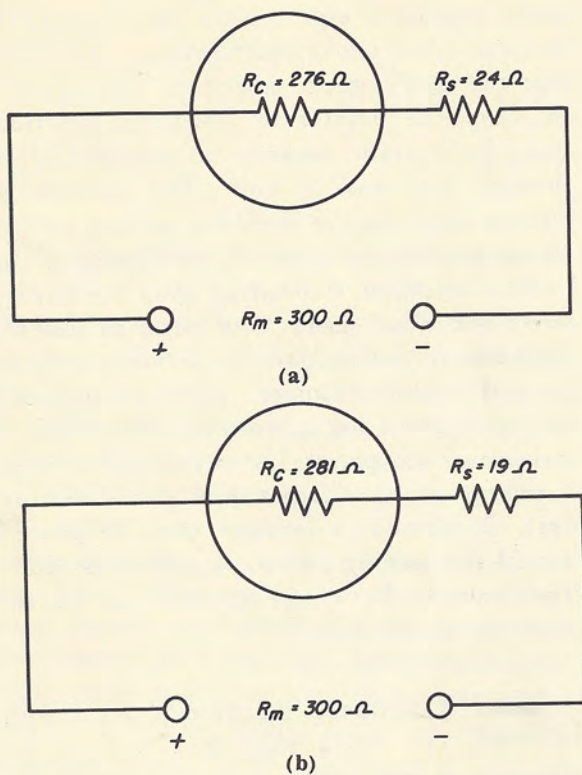


Fig. 11-6

the coil resistance, most manufacturers try to get the meter resistance as close to the standard as possible.

11-4. MOVEMENT USED AS VOLTMETER

Calculating Multipliers. If a 1-ma movement with 300 ohms resistance has 1-ma of current flowing at full scale, the voltage across the meter terminals may be found by using Ohm's Law:

$$\begin{aligned}
 E_m &= I_m \times R_m \\
 &= 0.001 \times 300 \\
 &= 0.3 \text{ volts}
 \end{aligned}$$

where:

E_m = voltage across meter terminals

I_m = current through meter

R_m = total resistance of moving coil and standardizing resistor

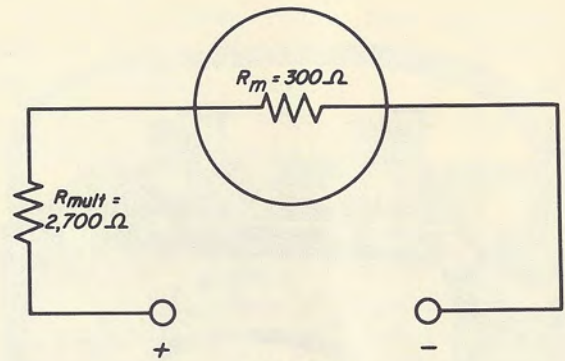


Fig. 11-7

If the same movement has 0.5 ma flowing through it, the voltage across the terminal is:

$$\begin{aligned}
 E_m &= I_m \times R_m \\
 &= 0.0005 \times 300 \\
 &= 0.15 \text{ volts}
 \end{aligned}$$

Thus, the meter measures not only current but voltage, too. To read voltage, all that is necessary is to calibrate the dial for voltage readings as well as current readings. However, a meter that measures only up to 0.3 volts is not of very much use to a serviceman. The voltage limit can be raised by placing a current-limiting resistor in series with the meter movement and the meter terminals. Figure 11-7 shows how this may be done. Such a current-limiting resistor is called a *multiplier* and is marked R_{mult} in the drawing. The value of the multiplier resistor is determined by the amount of voltage that is measured when the needle goes to full scale. The total series resistance of the meter and the multiplier added together must permit exactly 1 ma to flow. For example, if the full scale reading is to be 3 volts, then the total resistance (R_t) of the meter and the multiplier is found by using Ohm's Law:

$$\begin{aligned}
 R_t &= \frac{E}{I_m} \\
 &= \frac{3}{0.001} \\
 &= 3000 \text{ ohms}
 \end{aligned}$$

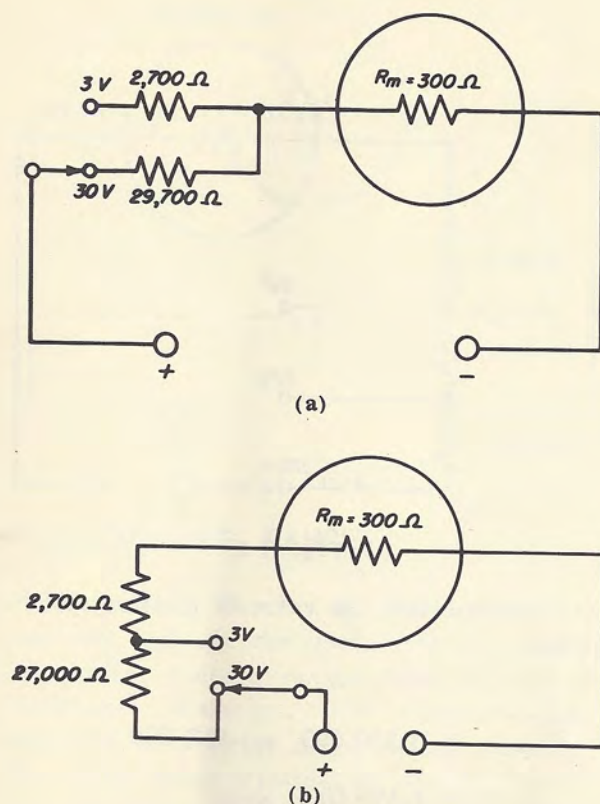


Fig. 11-8

If the total resistance of the meter and multiplier is 3,000 ohms, then the resistance of the multiplier is equal to 3,000 ohms *minus* the 300 ohms of the meter resistance, or 2,700 ohms ($3,000 - 300 = 2,700$). The circuit, as you can see in Fig. 11-7, is really a voltage divider. The meter, at full scale, has a voltage drop of 0.3 volt and the multiplier has a drop of 2.7 volts.

To increase the voltage range to 30 volts, we find R_t as follows:

$$R_t = \frac{30}{0.001}$$

$$= 30,000 \text{ ohms}$$

Then:

$$R_{\text{mult}} = R_t - R_m$$

$$= 30,000 - 300$$

$$= 29,700 \text{ ohms}$$

We could then hook up the meter circuit as shown in Fig. 11-8a. This would give us two useful voltage scales: 3 volts and 30 volts. However, a more practical method would permit us to use the 3-volt multiplier as part of the resistance of the 30-volt multiplier. This arrangement is shown in Fig. 11-8b. To find the value of resistance needed for the second multiplier, we subtract the sum of the meter resistance and the first multiplier from the total resistance of the 30-volt range:

$$30,000 - (300 + 2,700)$$

$$30,000 - 3,000 = 27,000 \text{ ohms}$$

As shown in the drawing, when the switch is in the 3-volt position, only the meter resistance and 2,700-ohm multiplier are in the circuit. When the switch is in the 30-volt position, the meter resistance, the 2,700-ohm multiplier, and the 27,000-ohm multiplier are all in series.

The voltage range may be extended to any reasonable value by making the following calculations:

1. Find the total resistance. The total resistance = $\frac{\text{full-scale voltage desired}}{\text{full-scale meter current}}$

2. Subtract the sum of the meter resistance and the total multiplier resistance (of the next scale lower) from the total resistance. The remainder equals the value of the new multiplier.

For example, to increase the voltage range of the meter from 30 volts to 150 volts, we first find the total resistance:

$$R_t = \frac{150}{0.001}$$

$$= 150,000 \text{ ohms}$$

Next we find the value of the new multiplier:

$$\begin{aligned}
 R_{\text{mult}} &= R_t - (R_m + \text{total multiplier resistance}) \\
 &= 150,000 - 30,000 \\
 &= 120,000 \text{ ohms}
 \end{aligned}$$

Figure 11-9 shows the new multiplier connected to the meter circuit.

Have you noticed that for the 3-volt range the total resistance was 3,000 ohms, for the 30-volt range it was 30,000 ohms, and for the 150-volt range it was 150,000 ohms? In each case the total resistance was equal to a thousand ohms for each volt of full-scale reading. For this reason, the sensitivity of meters that use a 1-ma movement is spoken of as being a thousand ohms per volt. To find the ohms-per-volt sensitivity of a meter, divide one volt by the amount of current necessary to drive the needle to full scale. For example, the meter in your multimeter is rated at 50 μa . To find the ohms-per-volt sensitivity, divide 1 by 0.00005a and get 20,000 ohms. Your meter, therefore, has a sensitivity rating of 20,000 ohms per volt.

High-Voltage Ranges. When voltage ranges above about 1,000 volts are made part of a meter, it is common practice to keep these high potentials away from the selector switch. This is done to prevent possible *arcing over* in the switch. (You know that when electrical pressure becomes great enough, electrons actually jump across from one terminal to another. We sometimes call this arcing over.) In such cases, as shown in Fig. 11-10, the positive test lead connects to a separate jack or terminal post that is connected directly to the high-voltage multiplier to take advantage of the air space between the post and switch lug.

To increase the voltage range of the meter from 150 volts to 1,500 volts, we must first find the total resistance, as before:

$$R_t = \frac{1,500}{0.001} = 1,500,000 \text{ ohms}$$

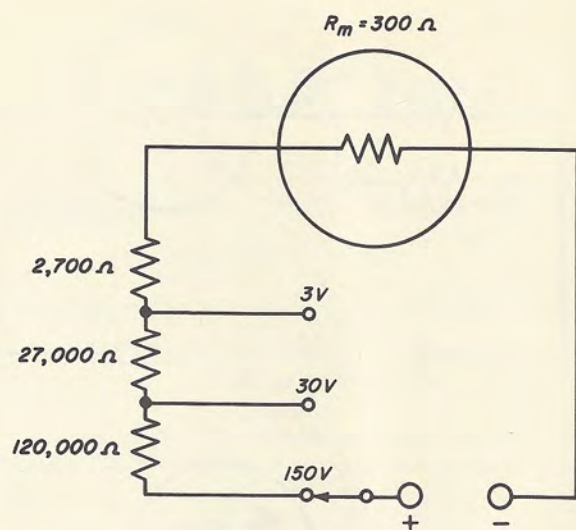


Fig. 11-9

Next we find the value of the new multiplier:

$$\begin{aligned}
 R_{\text{mult}} &= 1,500,000 - 150,000 \\
 &= 1,350,000 \text{ ohms}
 \end{aligned}$$

In addition to the use of special high-voltage jacks, high-voltage ranges call for special high-voltage test leads that have probes and test lead wire that can withstand the high potentials. Further instructions for making high-voltage tests are given in Service Practices 7.

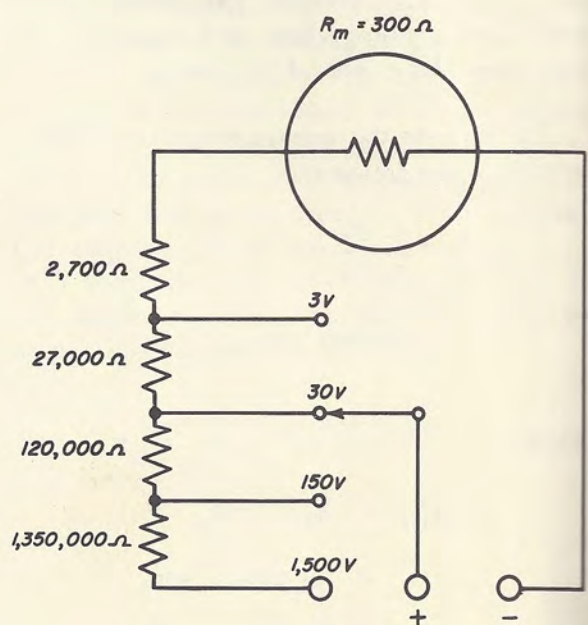


Fig. 11-10

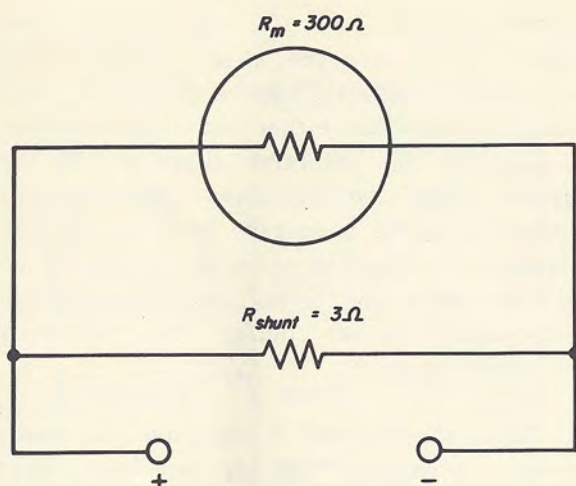


Fig. 11-11

11-5. CURRENT RANGES

Calculating Shunts. We have seen how we may increase the usefulness of a meter by adding voltage ranges with the aid of multiplier resistors. The current-reading capacity of a meter may also be increased by using *shunt-resistors* or *shunts*. Shunts are resistors in parallel with the meter movement. For example, in Fig. 11-11, a 3-ohm resistor is connected in parallel with a 300-ohm, 1-ma movement. As you know, the greater the resistance, the less is the current; and the less the resistance, the greater is the current. So, any current entering at the negative meter jack and leaving at the positive meter jack will divide between the meter and the shunt resistor, with the greater part going through the low-value shunt resistor. In fact, we can calculate exactly how much will flow in each, because the current will be in inverse proportion to the proportion of the meter resistance over the shunt resistance. The proportion of the meter resistance to the shunt resistance is:

$$\frac{300 \text{ (meter resistance)}}{3 \text{ (shunt resistance)}} = \frac{100}{1}$$

Inverted, this becomes:

$$\frac{1}{100} = \frac{\text{meter current}}{\text{shunt current}}$$

Therefore, at full scale the meter current is 1 ma, and the shunt current is 100 ma. The total current flowing through the meter and the shunt will be the sum of these, or 101 ma. Normally, we wouldn't have a 101-range. Usually, the value of a current range is rounded off to even zeroes or, in some cases, to multiples of five. So we might have ranges of 10, 20, and 100 ma, or 5, 10, 25, and 100 ma.

The calculation of the shunt resistance needed for any current range is easy to find if the full-scale current and the internal resistance of the meter are known. We use the formula:

$$R_{\text{shunt}} = \frac{R_m}{N-1}$$

where:

$$R_m = \text{meter resistance}$$

$$N = \text{number of times meter current is multiplied for new current range}$$

To use this formula, we must first decide what current range we want so that we may know how much N is. For example, let's find the value of shunt needed for a 10-ma range. Ten milliamperes is ten times one milliampere (the full-scale meter current), so N equals 10. Therefore, we divide the meter resistance by 10 minus 1. The number 1 is constant and remains the same, regardless of the full-scale meter current.

$$\begin{aligned} R_{\text{shunt}} &= \frac{R_m}{N-1} \\ &= \frac{300}{10-1} \\ &= \frac{300}{9} \\ &= 33\text{-}1/3 \text{ ohms} \end{aligned}$$

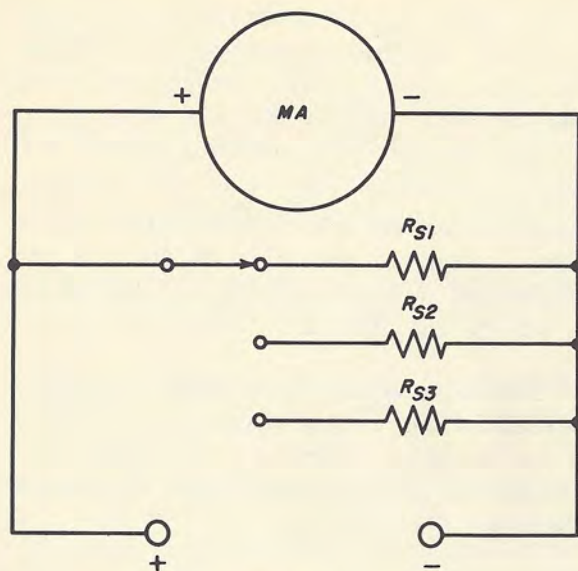


Fig. 11-12

To find the shunt necessary to measure 100 ma full-scale:

$$\begin{aligned}
 R_{\text{shunt}} &= \frac{R_m}{N - 1} \\
 &= \frac{300}{100 - 1} \\
 &= \frac{300}{99} \\
 &= 3\text{-}1/33 \text{ ohms}
 \end{aligned}$$

We have a choice of switching methods for adding shunt resistors to the meter. It is possible to use the very simple method shown in Fig. 11-12, but this method has certain serious practical disadvantages that make us look for a better way.

Consider what happens in the circuit when the switch arm is moved from one shunt resistor to another. While the arm is between contacts, the entire current flows through the meter only, and the meter may be damaged if the current exceeds the full-scale capacity of the meter movement. A switch of the *make-before-break* type can be used. When such a switch is used, the contact arm makes connection with the next shunt before breaking connection with the shunt from which it moves. So, for a short time, while the switch is changing to another

current range, both the old and the new shunt are across the meter. Because two resistors in parallel have a combined value that is less than either shunt resistor has separately, the effective shunt across the meter during the switching operation will cause the meter to receive less current than it would in either the old or the new position. In this way, the meter is protected from excessive current during the switching operation.

While this method is often used, it sometimes presents another problem. When switches have been in service a while, a small amount of resistance, called *contact resistance*, may appear between the contact arm and any switch point. The resistance is caused by oxidation of the metal surfaces of the switch and, sometimes, by dust and dirt. If the resistance of the shunt is very low, the contact resistance between the arm and the switch points may cause serious errors in the reading. This is true because the contact resistance is in series with the shunt, and thus adds to the actual resistance across the meter. This difficulty can be overcome by using a two-gang switch, as shown in Fig. 11-13. In this circuit, the contact resistance at 4A has no effect on the value of shunt R_{S4} , and the contact resistance at 4B is in series with the resistance

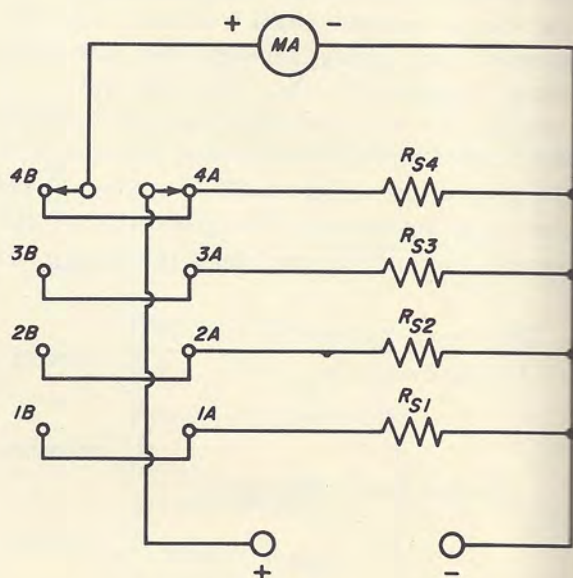


Fig. 11-13

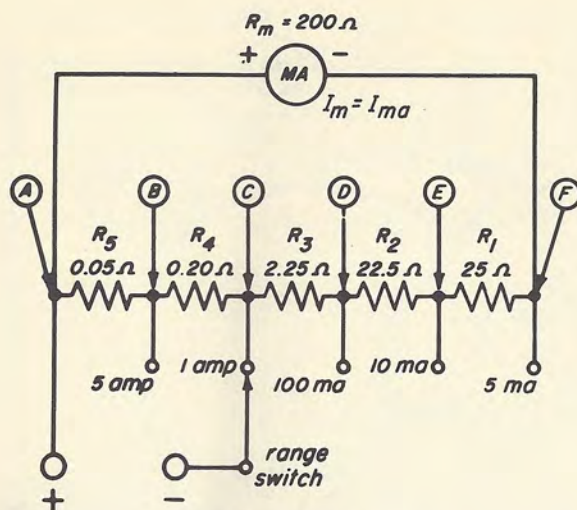


Fig. 11-14

of the meter movement. Because the meter resistance is much greater than the contact resistance, it does not cause any serious error.

Universal Shunt. Another method of connecting shunt resistors is known as the *universal shunt*. Figure 11-14 shows a typical universal shunt and switching system. Note that the resistors are all connected in series across the meter terminals and the line connection goes to the switch arm. Current from the line must go through the switch contact before it can reach the meter. If the switch contact fails, no current can reach the meter. But in the simple shunt of Fig. 11-12, if the switch contact fails while a measurement is being made, no current goes through the shunt, thus letting the entire current flow through the meter. This may result in meter damage. Thus, this feature of meter protection is an important advantage of the universal shunt. To calculate the proper values of the universal shunt, we must know the meter current needed for full-scale deflection, the meter resistance, and the current ranges needed. It is not possible to make a meter that needs 50 microamperes for full-scale deflection read full scale on 10 microamperes, so any new current ranges must be greater than the basic current range of the meter. Let's find the value of shunts needed if a 1-ma movement with a resistance of 200 ohms is to read full scale on 5 ma, 10 ma, 100 ma, 1 amp, and 5 amps. Since the lowest current range is to be 5 ma, and the meter requires 1/5 of this current (1 ma)

for full-scale deflection, the other 4/5 (4 ma) must pass through the shunt. We will assume that the meter resistance is 200 ohms. To find the value of this shunt, we use the formula:

$$R_{\text{shunt}} = \frac{R_m}{N-1}$$

$$= \frac{200}{5-1}$$

$$= 50 \text{ ohms}$$

The total series resistance of a universal shunt is always equal to the resistance of the shunt needed for the *lowest* current range. The current ranges of any practical ammeter are all multiples of the full-scale current of the basic meter movement. For example, take the five ranges we selected for the 1-ma movement: 5 ma is five times, 10 ma is ten times, 100 ma is 100 times, 1 ampere is 1,000 times, and 5 amperes is 5,000 times the basic meter current. We call these *multiplying factors*. We use them to find the value of each of the shunt sections. We use the formula:

$$R_{\text{section}} = \frac{R_{\text{shunt}} + R_{\text{meter}}}{N}$$

where:

$$N = \text{multiplying factor for the meter range}$$

$$R_{\text{shunt}} = \text{total shunt resistance across meter}$$

Let's find the value of the 10-ma section of the shunt:

$$R_{10 \text{ ma}} = \frac{50 + 200}{10}$$

$$= \frac{250}{10}$$

$$= 25 \text{ ohms}$$

The 100-ma section comes next:

$$R_{100 \text{ ma}} = \frac{50 + 200}{100}$$

$$= \frac{250}{100}$$

$$= 2.5 \text{ ohms}$$

The 1-amp section follows:

$$\begin{aligned} R_{1 \text{ amp}} &= \frac{50 + 200}{1,000} \\ &= \frac{250}{1,000} \\ &= 0.25 \text{ ohm} \end{aligned}$$

And finally the 5-amp section:

$$\begin{aligned} R_{5 \text{ amp}} &= \frac{50 + 200}{5,000} \\ &= \frac{250}{5,000} \\ &= 0.05 \text{ ohm} \end{aligned}$$

The resistance values we have just found show the actual value of shunt resistance across the input terminals for each current range. For example, when the range switch is in the 5-ma position, the entire 50-ohm shunt, *A-F*, is used. We found that the shunt for the 10 ma range is 25 ohms, so we find that when the switch is in the 10 ma position, 25 ohms is across the input terminals, *A-E*. To find the value of the first section, R_1 , we subtract the 25 ohms of the 10 ma section from the 50 ohms of the total shunt and get 25 ohms. The first section, R_1 , is therefore 25 ohms.

The 25 ohms that we use for the 10-ma shunt is divided into four sections for the remaining ranges. Therefore, to find R_2 (*D-E*), we subtract the 2.5 ohms of the 100-ma range from 25 ohms and get 22.5 ohms, the value of R_2 . To find R_3 (*C-D*), we subtract the 0.25 ohm of the 1-amp range from 2.5 ohms of the 100 ma range and get 2.25 ohms. To find R_4 (*B-C*) we subtract the 0.05 ohm of the 5-amp range from 0.25 ohm of the 1-amp range and get 0.20 ohm.

11-6. OHMMETER CIRCUITS

A moving-coil meter may be used to measure resistance, if a source of current is available. A simple ohmmeter circuit is shown in Fig. 11-15. It consists of a 1-ma

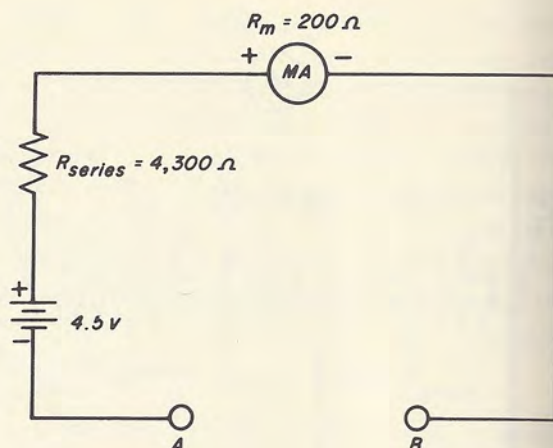


Fig. 11-15

meter in series with a current-limiting resistor and a 4.5-volt battery. The internal resistance of the meter is 200 ohms. The series resistor has a resistance of 4,300 ohms. This value was chosen so that the resistance of the meter added to the resistance of the series resistor would be just enough to limit the current flow to exactly 1 ma when connected across 4.5 volts. It was found by using Ohm's Law:

$$\begin{aligned} R_t &= \frac{E}{I} \\ &= \frac{4.5}{0.001} \\ &= 4,500 \text{ ohms} \end{aligned}$$

then:

$$\begin{aligned} R_{\text{series}} &= R_t - R_m \\ &= 4,500 - 200 \\ &= 4,300 \text{ ohms} \end{aligned}$$

If a wire of zero resistance is placed across terminals *A* and *B* in Fig. 11-15, exactly 1 ma will flow and the pointer will go to full scale. Therefore, an ohmmeter scale is marked zero ohms at the full-scale position and infinity (∞) at the zero-current position. When a resistor of unknown value (R_x) is placed across terminals *A* and *B*, the total series resistance is equal to 4,500 ohms added to resistance of R_x . The current is then less than one ma and the pointer does not go to full scale. For example, let's

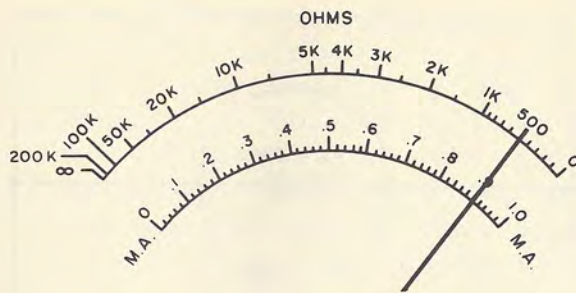


Fig. 11-16

assume that R_x equals 500 ohms. Then the total series resistance equals 5000 ohms. The current flowing through the meter is then 4.5 divided by 5,000 which equals 0.9 ma. Therefore, when the pointer rests on the 0.9 ma line on the meter scale, as shown in Fig. 11-16, it also rests on the 500-ohm line on the ohmmeter scale. If we now add another 500-ohms, making R_x 1,000 ohms, the total resistance becomes 5,500 ohms and the current is reduced to 0.818 ma. If we make R_x 1,500 ohms, the total resistance becomes 6,000 ohms and the current is reduced to 0.75 ma. When we add equal amounts of resistance, one after the other, it soon becomes clear that the movement of the meter pointer is not equal for each equal change in resistance. In other words, the typical ohmmeter scale is not linear.

In all practical ohmmeters, a rheostat makes up part of the series resistance. You remember, from your study of cells and batteries, that, as a cell becomes old and used up, the voltage delivered to a load (terminal voltage) drops below the rated value. When the terminal voltage of a cell used in an ohmmeter drops below its rated value, the series resistance is reduced by adjusting the series rheostat until the current flowing through the meter permits the needle to go to full scale. For example, if the battery voltage should drop to 4.2 volts, the total resistance needed to produce a current flow of 1 ma would be only 4,200 ohms. Therefore, the series resistor would need to be only 4,000 ohms instead of the 4,300 ohms necessary when the batteries are at

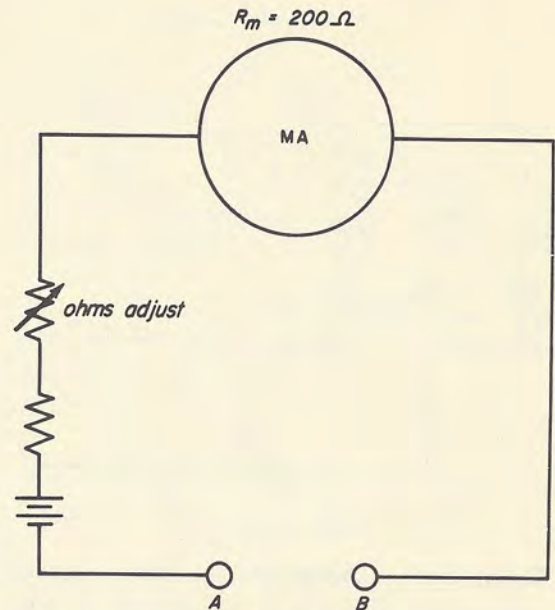


Fig. 11-17

full strength. Figure 11-17 shows the series resistor divided into two parts, one fixed and the other variable. The variable resistor is usually called the *ohms adjust* or *zero ohms control*.

In the instructions for reading meters given in Service Practices 7, you were told that ohmmeter readings near the center of the scale are most accurate. For this reason, most ohmmeters have two or more ranges. For example, if a second ohmmeter range were provided for your meter, with a multiplier factor of 10, then the pointer would rest at the half-scale position when a 45,000-ohm resistor was being measured. The scale shown in Fig. 11-16 would be used, with the difference that all readings would be multiplied by 10.

To provide such an ohmmeter range, the circuit shown in Fig. 11-18 might be used. Looking at the diagram, you can see that it would be necessary to change to a 45-volt battery and to increase the series resistance to 44,800 ohms. You can also see that if we wanted to add a 10-times higher range, it would be necessary to have 450 volts and a series resistor of 449,800 ohms. Such a meter would read 450,000 ohms at half-scale. However, because of the high voltages required, this method of providing several ohmmeter ranges is not practical.

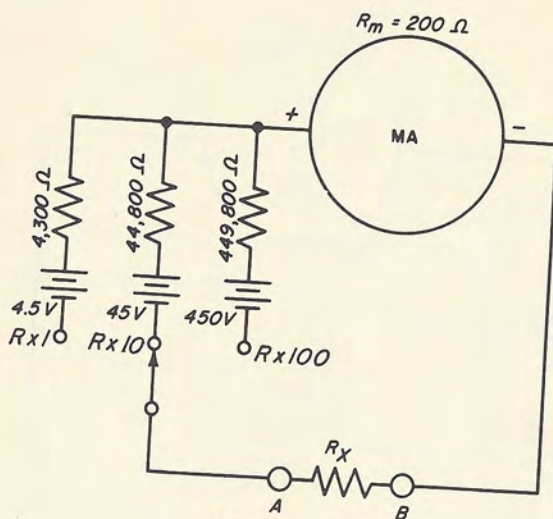


Fig. 11-18

Shunt-Type Ohmmeter. Another method of measuring resistance is shown in Fig. 11-19. It is called the *shunt-type ohmmeter* because the resistor being measured is placed in shunt with the meter movement. It uses a 1.5-volt dry cell instead of the 4.5-volt battery used in the other circuit. All that is necessary is to find the resistance that permits the flow of 1 ma when 1.5 volts is applied. From this, we subtract the resistance of the meter and the remainder is the resistance of the series resistor.

The operation of this circuit is simple. When the switch is closed, the needle reads full scale (infinity on the ohms scale). If terminals A and B are connected together with a wire, the meter is shorted out and the pointer will remain in the zero-current position, which reads zero on the ohms scale. This ohmmeter reads in a direction opposite to that of the series type discussed before; the low values of resistance are indicated on the left side of the dial and the high values on the right side. When a resistor is placed between A and B, the current divides; part goes through the resistor and part through the meter. For example, if R_x is equal to the meter resistance, half the current flows through the meter and half through R_x . The total current is 1 ma; therefore, the current of 0.5 ma flowing through the meter moves the pointer to half scale. When R_x equals 50 ohms, 4/5 of the current will flow through R_x and 1/5 through the

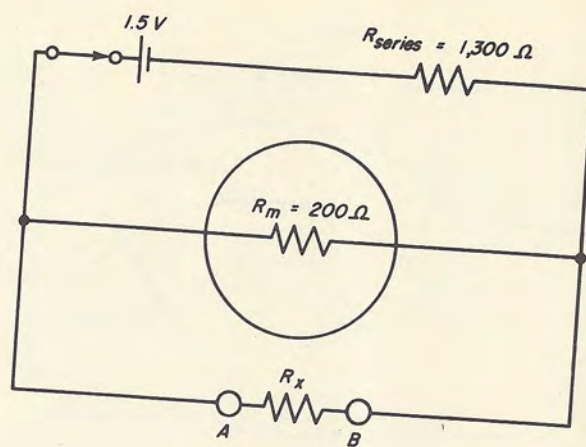


Fig. 11-19

meter. The pointer, therefore, will rest on the 0.2-ma calibration line.

A meter scale may be calculated for such an ohmmeter by using the formula:

$$I_m = \frac{R_x}{R_x + R_m} \times I_{fs}$$

where:

I_m = the position of the pointer on current scale

R_x = resistance of the resistor being measured

R_m = the meter resistance

I_{fs} = the current necessary for full-scale reading in amperes

For example, if the resistance of R_x is 400 ohms, then:

$$\begin{aligned} I_m &= \frac{400}{400 + 200} \times 0.001 \\ &= \frac{400}{600} \times 0.001 \\ &= \frac{2}{3} \times 0.001 \\ &= 0.00067 \text{ amp. or } 0.67 \text{ ma} \end{aligned}$$

The above formula is accurate enough for most purposes. But there is a slight error due to the fact that the total series resistance in the meter circuit changes whenever a resistor to be measured is placed in parallel with the meter. This error is greatest when very low values of resistance are being measured. The error can be eliminated by use of a more complex, but accurate formula:

$$I_m = \frac{R_m + R_{\text{series}}}{R_m + R_{\text{series}} + \frac{R_m \times R_{\text{series}}}{R_x}} \times I_{fs}$$

where:

I_m = position of pointer on current scale

R_m = meter resistance

R_{series} = resistance of current-limiting resistor in series with meter

R_x = resistance of resistor being measured

I_{fs} = current necessary for full-scale reading in amperes

For example, let $R_x = 4,500$ ohms; then:

$$\begin{aligned} I_m &= \frac{200 + 1,300}{200 + 1,300 + \frac{200 \times 1,300}{4,500}} \times 0.001 \\ &= \frac{1,500}{1,500 + \frac{260,000}{4,500}} \times 0.001 \\ &= \frac{1,500}{1,500 + 57.7} \times 0.001 \\ &= \frac{1,500}{1,558} \times 0.001 \\ &= 0.00096 \text{ amp or } 0.96 \text{ ma} \end{aligned}$$

This form of ohmmeter has one serious disadvantage; whenever the selector switch

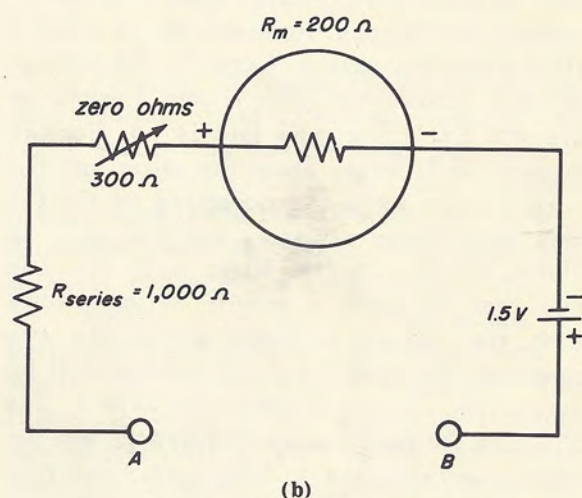
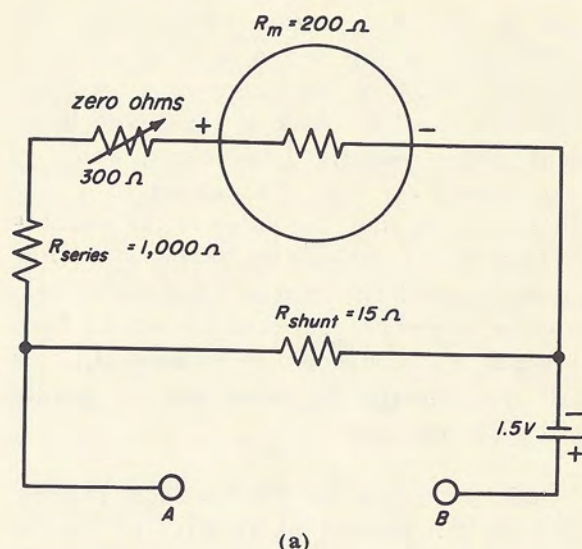


Fig. 11-20

is connected to such a range, the meter draws current. If the switch is left on, the meter may use up the battery before someone remembers to change the switch position.

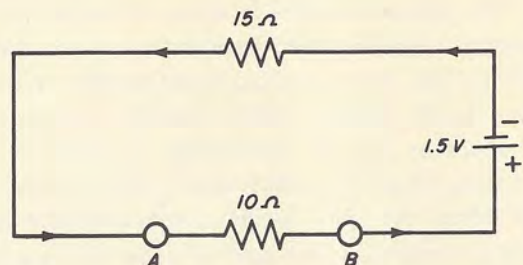
Voltage-Divider Ohmmeter. Another type of ohmmeter, sometimes called a voltage-divider ohmmeter, reads in the same direction as the series-type ohmmeter and has calibrations that are more nearly linear than either of the types just discussed. Figure 11-20a shows the basic circuit. Because the same circuit is used in the ohmmeter section of your multimeter, you should know how it works. At first glance, it looks complicated, but it isn't really — as you will see. Let's take the circuit apart and see what each part does. In Fig. 11-20b, we have left out the 15-ohm shunt resistor so that we can

look at the rest of the circuit first. The 1,000 ohms of the series resistor added to the 300 ohms of the zero-ohms resistor added to the 200 ohms of the meter movement makes exactly 1,500 ohms, which is just enough to limit the current to 1 ma. (In actual practice, the value of the variable resistor would probably be 500 ohms to allow for the possibility that a fresh cell might produce slightly higher than 1.5 volts.) When terminal *A* is connected to terminal *B*, 1 ma will flow through the meter and the needle will go to full scale.

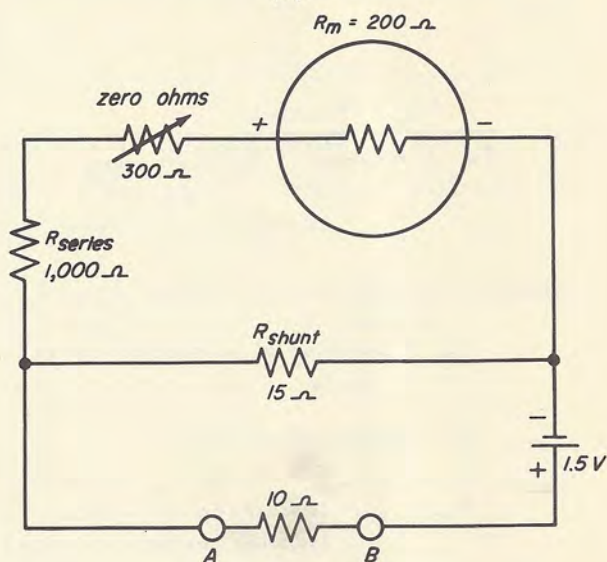
Now let us put the 15-ohm shunt resistor back in the circuit, as in Fig. 11-20a. So long as the circuit remains open at *A* and *B*, nothing will happen. However, let us place a 10-ohm resistor across *A* and *B*. The voltage divides across the 10-ohm and 15-ohm resistors. Let's see why this is so. For the moment we'll forget about the meter and the series resistors and concentrate on the 15-ohm and 10-ohm resistors and the cell, as shown in Fig. 11-21a. Right away you can see that we have a simple series circuit with the voltage divided across the two resistors. Three-fifths of the voltage will be across the 15-ohm resistor (because it has 15/25 of the total series resistance) and the remaining two-fifths will be across the ten-ohm resistor. So, 0.9 volt will appear across the 15-ohm resistor and 0.6 volt across the 10-ohm resistor.

Let's put the meter and series resistors back in the circuit, as in Fig. 11-21b. Remember that 0.9 volt appears across the meter circuit. The needle can no longer go to full scale. Instead it will go only 3/5 of the way, as in Fig. 11-21c. On the ohms scale, this is shown as the 10-ohm calibration point.

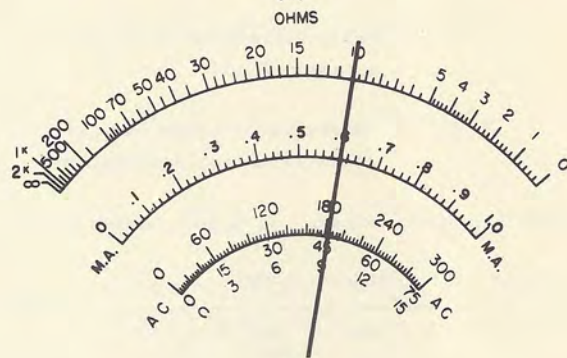
If we place a 15-ohm resistor across *A* and *B*, then the voltage will divide evenly across each of the 15-ohm resistors, the meter will receive half the full-scale current, and the needle will come to rest at the middle of the scale. Therefore, the 15-ohm calibration is at half-scale.



(a)



(b)



(c)

Fig. 11-21

We can go on and calibrate the entire ohmmeter scale by placing standard values across terminals *A* and *B* and figuring how much of the voltage will appear across the 15-ohm shunt resistor. Naturally the calibrations are crowded together at the left-hand side of the scale. So, if we wanted to add an $R \times 100$ range, it would seem that we would just multiply the 15 ohms of the shunt resistor by 100 and get 1,500 ohms. But it wouldn't work. Let's see why this is so.

First let's go back to the circuit with

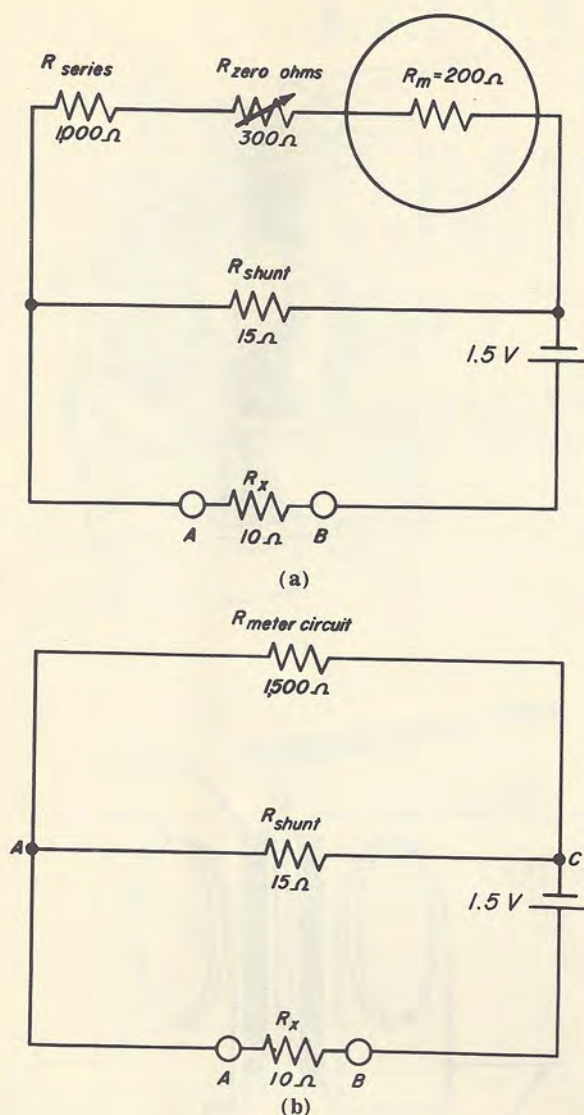


Fig. 11-22

the 15-ohm shunt in it. As before, we'll place a 10-ohm resistor across terminals A and B. Figure 11-22a shows the circuit and the resistance of each unit in the circuit. We can see that the meter circuit has a total of 1,500 ohms resistance. So, in Fig. 11-22b, this part of the circuit is shown as a single resistor of 1,500 ohms. In this simplified drawing of the circuit, we can see that the 1,500 ohms of the meter is actually in parallel with the 15-ohm shunt resistor. Therefore the amount of resistance between A and C is slightly less than 15 ohms. However, from your study of d-c circuits and meter loading, you know that when two resistors are in parallel, and one has more than ten times the resistance of the other, the total resistance of the two in parallel is

practically the same as the resistance of the one with the smaller resistance. In the case of our ohmmeter circuit, the meter circuit resistance is 100 times the resistance of the 15-ohm shunt, so for practical purposes we can say that the resistance between A and C is 15 ohms. But if we place a 1,500-ohm shunt instead of the 15-ohm shunt, we will have 1,500 ohms in parallel with 1,500 ohms. With a little figuring, we can see that the resistance of these two in parallel is 750 ohms. As a result, we would not get an $R \times 100$ range but would get an $R \times 50$ range instead. So, normally, we would shift to simple series-resistor ohmmeter circuits for the higher ranges and use the voltage-divider circuit only for the low ohms range.

In choosing the value of the shunt used in the voltage divider, we must consider two facts. One fact is that the lower the value of the shunt that is used, the more accurate are the readings of low values of resistance. Whatever value we choose will determine what the half-scale calibration point will be. For example, if we use a 5-ohm shunt, the half-scale calibration will be 5 ohms. Here's where the second factor comes in. The lower the value of the shunt that is used, the greater will be the load on the cell or battery that powers the ohmmeter. So, normally we select a value of shunt that draws a reasonable amount of current from the cell or battery.

11-7. POWER MEASUREMENT

The amount of d-c power consumed in a load, such as an electric heater or lamp, may be found by measuring the voltage across the load and the current flowing through the load and multiplying the values together. However, it is possible to make a meter that does this directly. With such a meter, called an electrodynamometer-type wattmeter, we can read the power in watts directly from the meter dial without arithmetic and separate voltage and current measurements. A typical wattmeter, calibra-

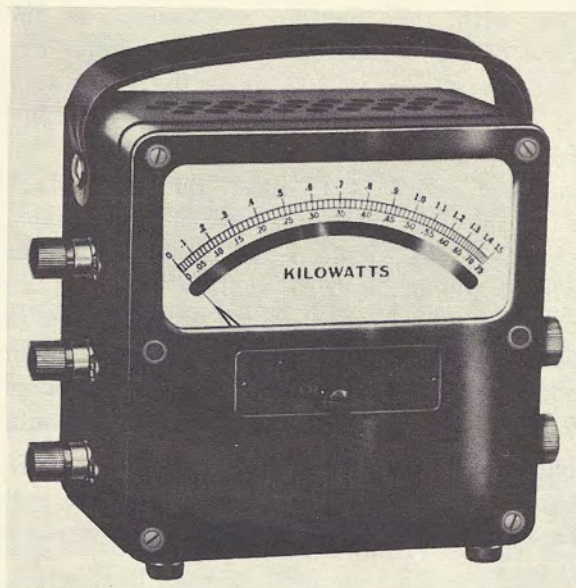
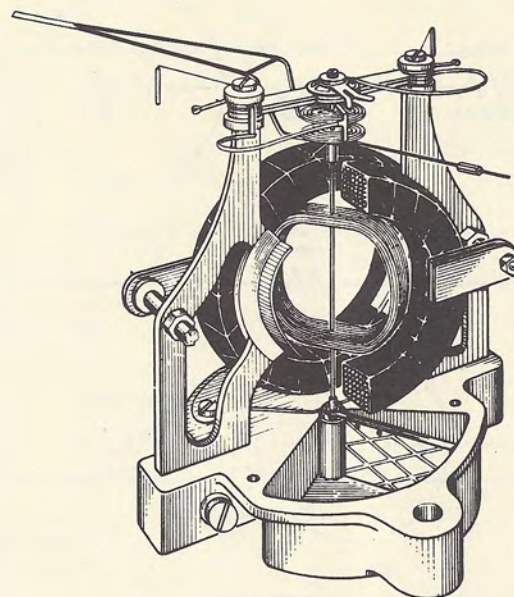


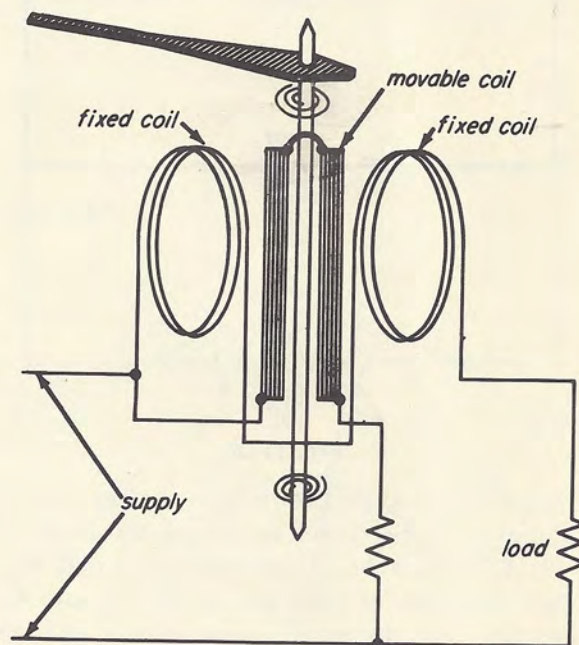
Fig. 11-23

ted in kilowatts, is shown in Fig. 11-23.

In the meters discussed so far, the field has been supplied by a permanent magnet, so that only the changes in the current flowing through the moving coil caused changes in the movement of the needle. The electro-dynamometer does not use a permanent magnet. Instead, a fixed coil carrying current provides the field for the moving coil. Figure 11-24a shows a cutaway view of the basic movement. As you can see, the fixed coil is divided into two parts, one on each side of the moving coil. The current flowing in the load flows through the fixed coil and provides the field for the moving coil. As shown in Fig. 11-24b, the voltage across the load is connected through a high-value resistor (multiplier) to the moving coil. With these connections, the field set up by the fixed coil is in proportion to the current and the field set up by the moving coil is in proportion to the voltage. The two fields combine to force the needle to a position of the



(a)



(b)

Fig. 11-24

calibrated meter face that represents a certain amount of power in watts.